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## Millimeter Waves for Broadband Satellite Communication 75- 98 GHz

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### **Abstract**

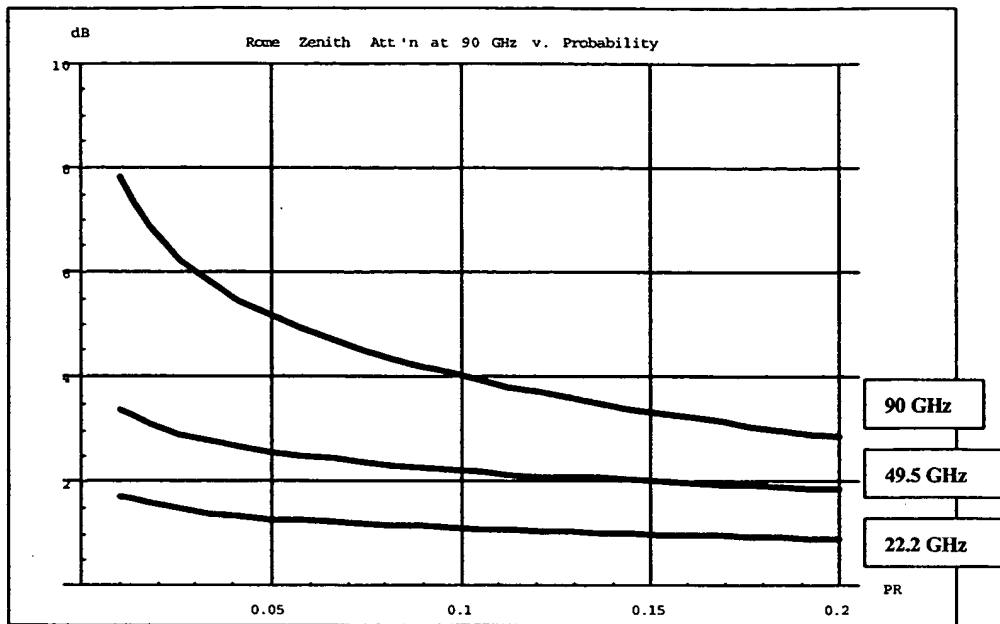
*We extend a four dimensional satellite attenuation model to five dimensions, with the aid of an exponential probability variable. Millimeter wave satellite communication in the 75-98 GHz region is indicated to be attractive for most of the Temperate Zone, with a 90% non rainy condition.*

### **1. Background**

Gaseous attenuation for satellite links was derived [1] in the early '80s [Appendix] by integrating terrestrial attenuation equations over the changing pressure as a function of altitude. These new results were conceptual and practical improvements over terrestrial attenuation equations which are often used for satellite communication. The integrated equations were intended to start a global attenuation model, but unknown cloud attenuation and water vapor attenuation stymied attempts at global attenuation models in the early '80s.

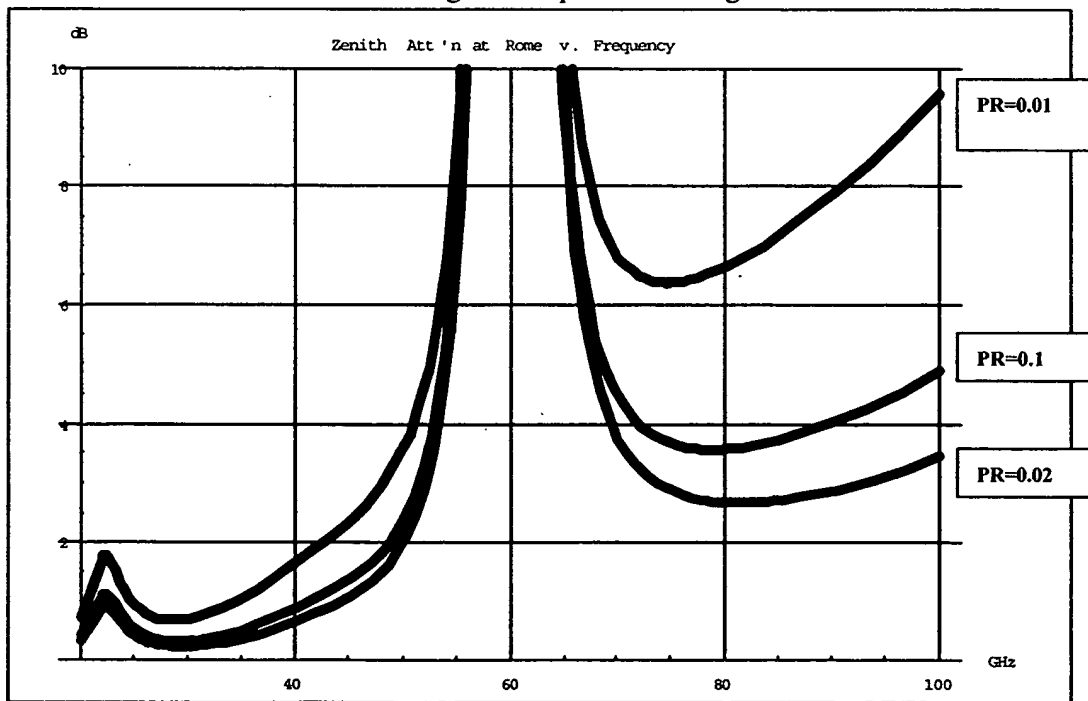
Fortunately, the Foundation Ugo Bordone used the invaluable Italsat results to derive global attenuation results at several important frequencies [2]. The integrated gaseous attenuation equations [1] could then be reexamined to see if they could yield a global attenuation model over a wide range of frequencies. The zenith attenuation maps shown by Barbaliscia, Boumis, and Martellucci for 49.5 and 22.2 GHz 99% non rainy conditions were especially valuable: They could be compared to the integrated gaseous attenuation for a satellite link. The excess attenuation implied by the FUB studies was then attributed to water vapor and clouds [3]. The attenuation maps at 49.5 and 22.2 GHz were then solved simultaneously for cloud and water vapor attenuation at 22.2 GHz. The simultaneous solution was done at all points on the map. This allowed a functional description (actually, two functional descriptions: One long, and one short shown in the appendix of the '99 paper) of zenith attenuation as a function of Longitude, Latitude, and frequency for frequencies in the 6 to 100 GHz range. This 4 dimensional attenuation function was very helpful directly and indirectly. It indicated that satellites with high elevation angles [4, 5] would offer promising performance for frequencies greater than 40 GHz in much of the Temperate Zone. Frequencies greater than 80 GHz were indicated to be attractive for Latitudes greater than 50N.

The question of communication in less severe attenuation remained unresolved. Here, we examine an earlier Italsat analysis [6] and find that cloud and vapor attenuation follow well behaved exponential probability density functions (pdf). We derive a new global equation for attenuation: It raises the prior four dimensional equation to five, with the new probability variable (Appendix). That is, zenith attenuation will be expressed as a function of Longitude, Latitude, frequency, and probability. The new probability dimension might be examined locally by choosing a single location, as Rome in Fig 1-1, where the bottom two curves (22, 49.5 GHz) may be compared directly with the FUB 1997 paper [6]. The top curve was derived.



**Fig. 1-1 Zenith Attenuation at Rome as a Function of Probability PR**  
**With Non Rainy Availability= 1-PR**

The results can be seen across a range of frequencies as Fig. 1-2.



**Fig. 1-2 Zenith Attenuation at Rome v. Frequency** May1devAEQNc.nb

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The five dimensional zenith attenuation function can also be seen as global maps for constant probability PR. It can be shown as Fig. 1-3 for PR=0.01 at 90 GHz, as it was in Sicily [3]. Fig. 1-4 may be compared at PR=0.1, as the 90% non rainy condition.

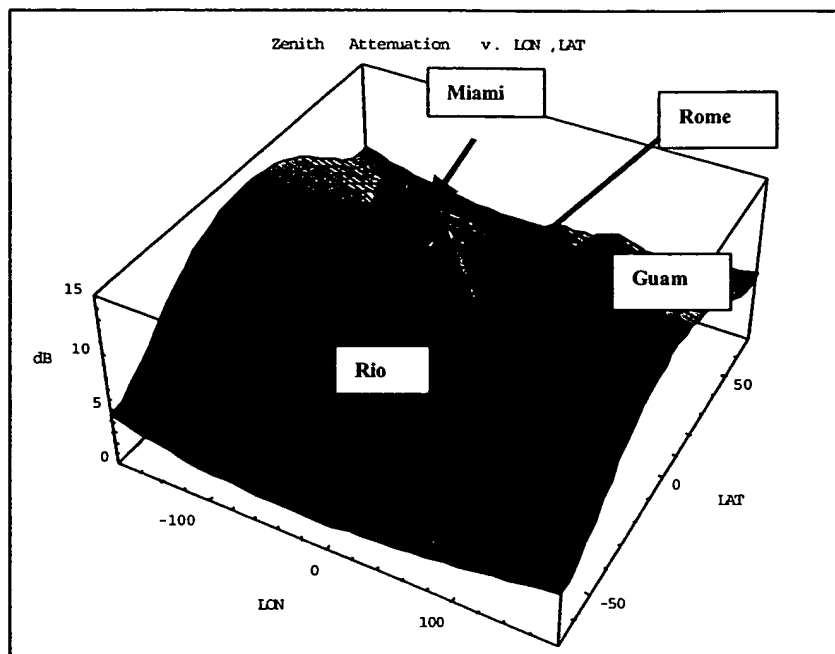


Fig 1-3 Zenith Attenuation at 90 GHz PR=0.01

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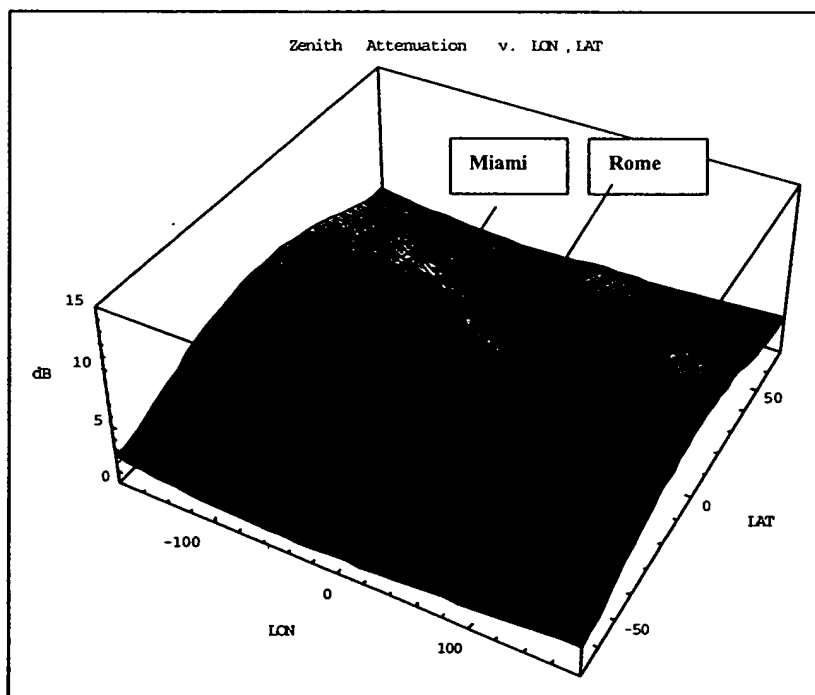
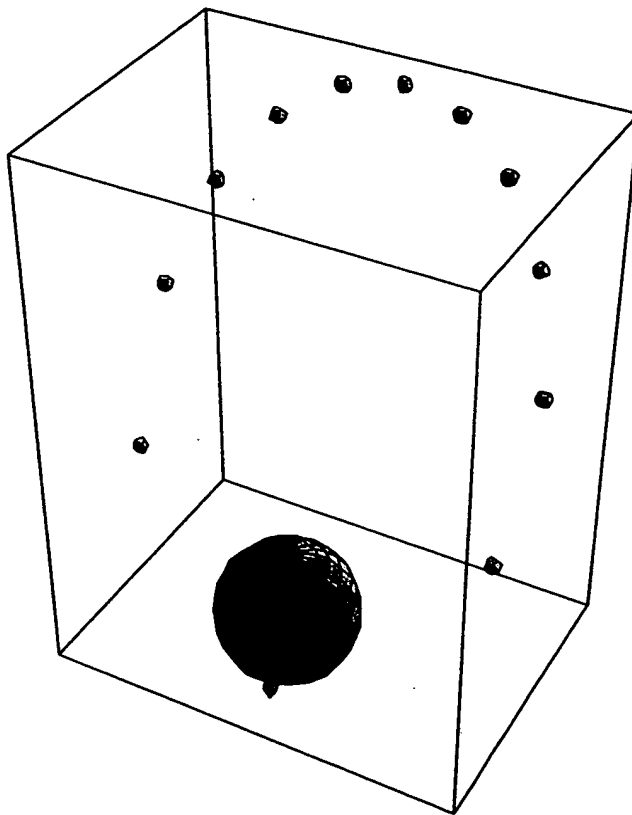


Fig. 1-4 Zenith Attenuation at 90GHz, 90% Non Rainy PR=0.1

## 2. Attenuation for High Elevation Satellite Systems

The zenith attenuation of the prior section must be weighted by the atmospheric path length, or closely as  $\text{Cosecant}[\text{elevation angle}]$ . Zenith attenuation near 10 dB at New York for 90 GHz in Fig. 1-3 would be doubled to 20 dB for a 30 degree elevation to a satellite. Some geosynchronous satellites do indeed present 30 degree elevation to New York, so 20 dB might be foreseeable for a 90 GHz New York link to a GEO. This attenuation would be debilitating for a millimeter wave system, and we ask if there could be any relief from high elevation systems. The Molniya satellite was conceived by the Soviets as an outstanding high elevation satellite in the mid- 1960s. It may be seen at one hour intervals of its 12 hour orbit in Fig. 2-1.



**Fig. 2-1 Inclined Elliptic Molniya Orbit, at 1 Hour Intervals**

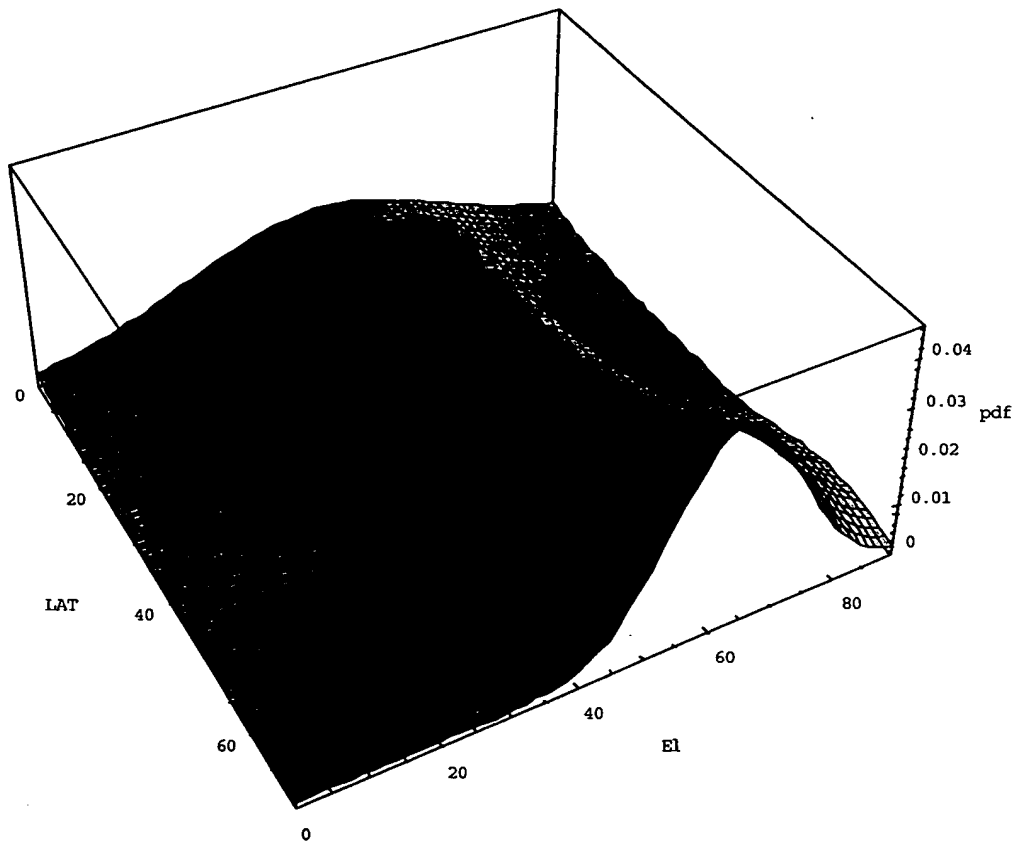
The Cleveland paper [4] discussed a system of 3 phased Molniya satellites to deliver high elevation angles in the Northern Temperate zone. It added two geostationary satellites for complementary coverage at low latitudes, for a five satellite system called a MolniyaGEO system, for lack of a better descriptor. The elevation angles are consistently high: An elevation probability density function may be shown as Fig. 2-2.

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The elevation pdf as a function of Latitude (LAT) is

$$e = \frac{\left( \frac{-47.0509 + 0.165865 \text{ LAT} + 0.00512491 \text{ LAT}^2 - 0.000520006 \text{ LAT}^3 + 5.22822 \times 10^{-6} \text{ LAT}^4 + x}{2 \left( -160.041 + 181.722 e^{-\frac{\text{LAT}^2}{900}} - 0.776901 \text{ LAT} + 0.270942 \text{ LAT}^2 - 0.00526509 \text{ LAT}^3 + 0.000029238 \text{ LAT}^4 \right)^2} \right)^2}{\left( -160.041 + 181.722 e^{-\frac{\text{LAT}^2}{900}} - 0.776901 \text{ LAT} + 0.270942 \text{ LAT}^2 - 0.00526509 \text{ LAT}^3 + 0.000029238 \text{ LAT}^4 \right) \sqrt{2\pi}} \quad (3-1)$$

p • E, Lat • ; 3 Molniya • 2 Geo sats .



**Fig. 2-2 MolniyaGEO Elevation PDF v. Latitude, Elevation**

Average elevation is close to 60 degrees at 60N, and more importantly high elevation as 50 degrees is seen at New York City near 40 North. The average cosecant[elevation] at each latitude can be found, and multiplied by zenith attenuation to find representatively higher satellite attenuation. The satellite attenuation south of 20N would be clearly higher than the zenith attenuation: 60% extra attenuation [dB] would be expected on the best MolniyaGEO path at 20N. The most useful parts of the Temperate Zone would include regions between 30N to 60N. We note that NY City and Rome are near 40N.

### 3. Optimum Frequencies

We saw in Cleveland [4] that attenuation could be described for a wide range of frequencies for 99% non rainy conditions. Fig. 3-1 shows examples for Guam, Rome, and Oslo. Net loss, formed from (Attenuation- Gain at Constant Aperture) could be described as Fig. 3-2.

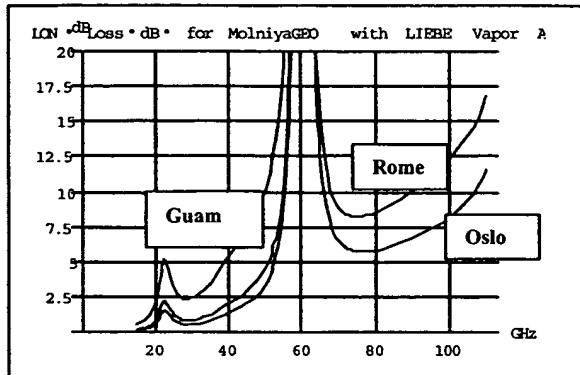


Fig. 3-1 Loss v. F at Guam, Rome, Oslo MolniyaGEO System

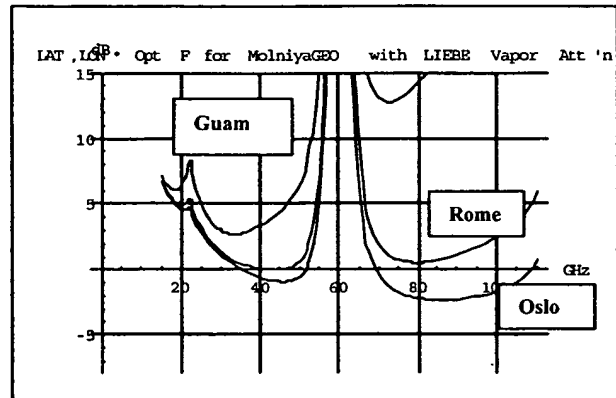


Fig. 3-2 Net Loss at Guam, Rome, Oslo MolniyaGeo System

Fig. 3-2 includes the typical frequency squared term for gain at constant aperture. We note that beamwidth would be reasonable even at 80 GHz for dish diameter as 0.2 - 0.5 meter. Attractive frequencies are indicated at 44 GHz and 79 GHz for Rome: Which one to choose? A global minimization would favor the 44 GHz solution for Rome, but we will see below that the less severe 90% non rainy attenuation found here will favor the higher frequencies.

Figures 3-3 and 3-4 relieve the 99% non rainy attenuation to 90%, while retaining the other features of 3-1 and 3-2. Optimum frequency at Rome is indicated as 90 GHz.

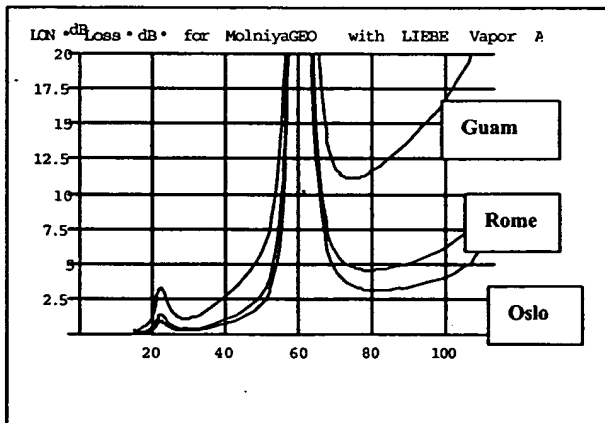


Fig. 3-3 Loss v. F at Guam, Rome, Oslo MolniyaGEO System; 90%

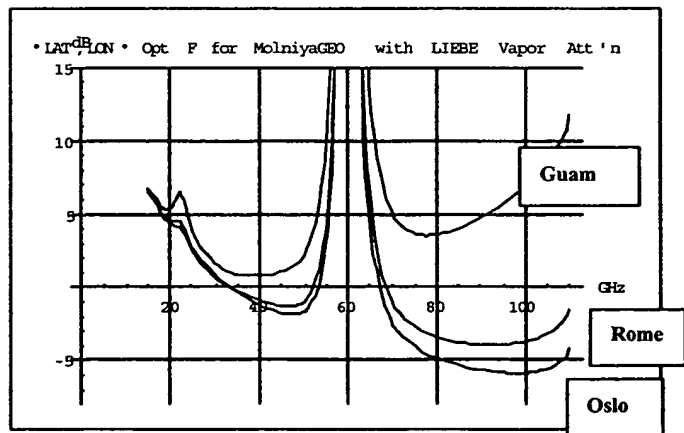
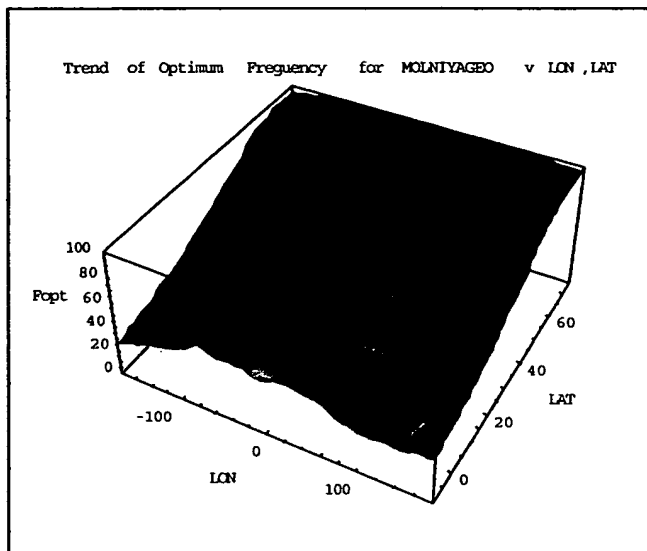


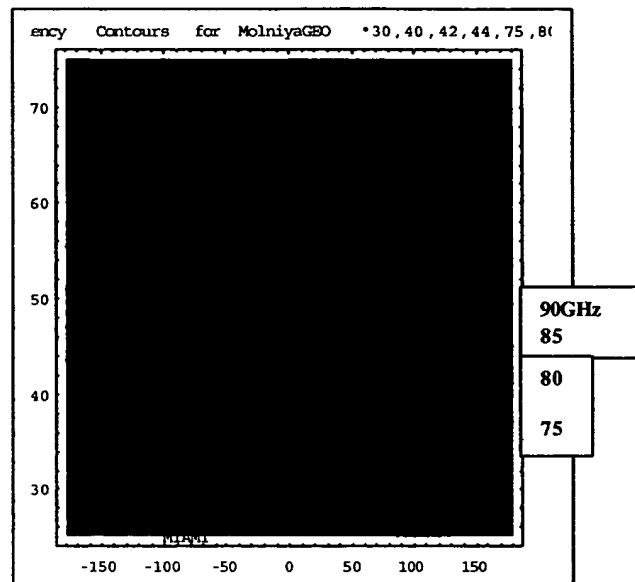
Fig. 3-4 Net Loss at Guam, Rome, Oslo MolniyaGeo System; 90%

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The trend of optimum frequencies can be found after a worldwide search, using each location for a decision as we did in Fig. 3-4. The result of the search, and subsequent curve fit to accommodate the sudden shifts past the 60 GHz oxygen line, can be seen as Fig. 3-5. Miami and Guam represent are shown as low frequencies, but most of the temperate zone north of 30N has attractive frequencies greater than 72 GHz.



**Fig. 3-5 Optimum Frequency Topography**  
90% Non Rainy Conditions PR=.1



**Fig. 3-6 Optimum Frequency Contours**  
90% Non Rainy Conditions

NY City and Rome are indicated in Fig. 3-6 to have optimum frequencies near 85 GHz, as opposed to the closer indication as 90 GHz of Fig. 3-4.

### Conclusions

We have extended the 99% non rainy attenuation global attenuation function to include less severe attenuation conditions, as a function of probability. This has raised the dimensionality of the zenith attenuation equation from four to five. The equations are long, and are included in a companion paper [7] and more conveniently on a floppy.

The 90% non rainy condition was indicated here to allow 75- 85 GHz frequencies to be used advantageously throughout much of the Temperate Zone. However, the 90% attenuation level would need help to bring it up to even modest availability requirements of VSAT stations. A Soviet cloud autocorrelation function [8] indicates this could be done with site separation on the order of 40 km.

### Acknowledgements

W. T. Brandon was the key organizer of Ka band projects at the Mitre Corp. in the early 1980s. He and Ed Bedrosian of the RAND Corporation offered invaluable insights in discussions of satellite orbits for Ka band systems.

## Selected References

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8. Boldyrev and Tulupov, Cloud Correlation Function, COSPAR Space Research XI, Leningrad USSR 20-29 May 1970, Vol. 1 Akademie-Verlag Berlin, 1971.

## Appendix Gaseous Attenuation for Satellite Link

Unlike most gaseous attenuation treatments, we do not use the specific attenuation at sea level directly. Instead, we note that both the line width and amplitude are pressure dependent and the general attenuation as a function of altitude looks very different than the specific attenuation at sea level.

The specific attenuation for oxygen at sea level may be found by Van Vleck and Bean and Dutton to be of the form

$$\gamma_l = \frac{A \left[ \frac{\cdot \cdot 1}{\cdot \cdot 1^2 \cdot \frac{1}{\cdot 2}} \cdot \frac{\cdot \cdot 2}{\cdot \cdot 2^2 \cdot \cdot 2 \cdot \frac{1}{\cdot 2}} \cdot \frac{\cdot \cdot 2}{\cdot \cdot 2^2 \cdot \cdot 2 \cdot \frac{1}{\cdot 2}} \right]}{\cdot 2} \quad \text{dB/km} \quad (\text{A-1})$$

where the linewidths  $\Delta \nu_1 = 0.018 \text{ cm}^{-1} \text{ atm}^{-1}$ ,  $\Delta \nu_2 = 0.012 \text{ cm}^{-1} \text{ atm}^{-1}$  by Liebe  
and  $\lambda$  is wavelength in cm.  
 $A = 0.34$

The appropriate form for oxygen attenuation as a function of altitude  $h$  would be:

$$\gamma_l = \frac{A \cdot \frac{h}{H_0} \left[ \frac{\cdot \cdot \frac{h}{H_0} \cdot \cdot 1}{\cdot \cdot \frac{2h}{H_0} \cdot \cdot 1^2 \cdot \frac{1}{\cdot 2}} \cdot \frac{\cdot \cdot \frac{h}{H_0} \cdot \cdot 2}{\cdot \cdot \frac{2h}{H_0} \cdot \cdot 2^2 \cdot \cdot 2 \cdot \frac{1}{\cdot 2}} \cdot \frac{\cdot \cdot \frac{h}{H_0} \cdot \cdot 2}{\cdot \cdot \frac{2h}{H_0} \cdot \cdot 2^2 \cdot \cdot 2 \cdot \frac{1}{\cdot 2}} \right]}{\cdot 2} \quad \text{dB/km} \quad (\text{A-2})$$



where the exponential atmosphere has been substituted for the linewidths to account for pressure broadening and amplitude terms. This form has been integrated [1] in closed form for a ground station at altitude  $h_1$ (km) to  $\infty$ , as Eq. A-3.

$$A_{02} \cdot \frac{1}{\cdot 2} \left| A_{H0} \right| \frac{\log \left| \frac{\cdot 2 \cdot \frac{1}{\cdot 2} \cdot 2}{\cdot \frac{2 h_1}{H0} \cdot \cdot 2^2 \cdot \cdot 2 \cdot \frac{1}{\cdot 2} \cdot 2} \right|}{2 \cdot \cdot 2} \cdot \frac{\log \left| \frac{\cdot 2 \cdot \frac{1}{\cdot 2} \cdot 2}{\cdot \frac{2 h_1}{H0} \cdot \cdot 2^2 \cdot \cdot 2 \cdot \frac{1}{\cdot 2} \cdot 2} \right|}{2 \cdot \cdot 2} \cdot$$

$$\frac{\log \left| \frac{1}{\cdot \frac{2 h_1}{H0} \cdot \cdot 1^2 \cdot \frac{1}{\cdot 2} \cdot 2} \right|}{2 \cdot \cdot 1} \left| \right| \left| \right|$$

dB (A-3)

The scale height  $H_0$  is typically in the 7 to 8 km range. The 1.2 dB result at 49.5 GHz was necessary for solving the Foundation Ugo Bordone's attenuation maps [2,6]. Integrated water vapor considerations were also included in [1], as (A-4).

$$A_{h20} \cdot \frac{1}{\cdot 3 \cdot 2} \left| 0.0035 H_0 \cdot 0 \right| \cdot \frac{\cdot \frac{1}{\cdot 2} \cdot \frac{1}{\cdot 2} \cdot 2 \cdot \tan^{-1} \left| \frac{\cdot \frac{h_1}{H0} \cdot \cdot 3}{\cdot \frac{1}{\cdot 2} \cdot \frac{1}{\cdot 2} \cdot 2} \right|}{\cdot \frac{h_1}{H0} \cdot \cdot 3} \cdot \frac{1}{\cdot 2} \cdot \frac{1}{\cdot 2} \cdot 2 \cdot$$

$$\frac{2}{3} \cdot \frac{2 h_1}{H0} \cdot \frac{\cdot \frac{1}{\cdot 2} \cdot \frac{1}{\cdot 2} \cdot 2 \cdot \tan^{-1} \left| \frac{\cdot \frac{h_1}{H0} \cdot \cdot 3}{\cdot \frac{1}{\cdot 2} \cdot \frac{1}{\cdot 2} \cdot 2} \right|}{\cdot \frac{h_1}{H0} \cdot \cdot 3} \left| \right| \left| \right|$$

dB

(A-4)

and longer water vapor considerations were included in the paper at Taormina, Sicily. More convenient results are available on a floppy disk.